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14. ABSTRACT

An experimental and computational study was completed on the structure of two sets of flames: a *nonsooting* CH_4 counterflow diffusion flame doped with 1000 ppm of either jet fuel or a 6-component surrogate and a well-defined baseline C_2H_4 flame under incipient sooting conditions perturbed with the addition of 2000 ppm by mole of either jet fuel or two surrogates, a 6-component Utah/Yale blend and a two-component Aachen surrogate. Gas samples were extracted from the flame with quartz microprobes for subsequent GC/MS analysis. Profiles of critical fuel decomposition products and soot precursors, such as benzene and toluene, were compared. The data for C7-C12 alkanes were consistent with typical decomposition of large alkanes with both surrogates showing good qualitative agreement with jet fuel in their pyrolysis trends. Olefins were formed as the fuel alkanes decomposed, with agreement between the surrogates and jet fuel improved for small alkenes. Good agreement between jet fuel and the surrogates was found with respect to critical soot precursors such as benzene and toluene. Although the 6-component Utah/Yale surrogate performed better than the Aachen surrogate, the latter performed adequately and retained the advantage of simplicity, since it consisted of only two components. Additional work focused on the development of a domain decomposition parallel solution methodology for coflow diffusion flames.

15. SUBJECT TERMS

jet fuel surrogate, counterflow flames, gas chromatograph, parallel computing

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COMPUTATIONAL AND EXPERIMENTAL STUDIES OF JET FUEL COMBUSTION

Final Report

FA9550-06-1-0018

OVERVIEW

The "single fuel for the battlefield" is evolving into "jet fuels for the battlefield" (JP-8/JP-8+100/Jet-A/Jet A-1). They are planned to be the logistic fuels for all U.S. military operations through the year 2025. As a result, for the next two decades jet fuel will continue to play a central role in US Air Force operations from both a logistical and an economic viewpoint. In addition, the Air Force is interested in understanding the relationship between fuel properties and combustion behavior so as to be able to utilize future alternative fuels. The impact of this commitment extends into R & D activities as well. To an increasing extent, computational models are being used in the design of engineered systems such as aeropropulsion gas turbines (GTs). In addition, computational models are being developed to help understand issues related to post crash fires and projectile induced ignitions of JP-8 with the goal of enhancing aircraft survivability. This trend will continue as models improve, computer power increases, and the alternative of empirical testing becomes more expensive. Central to any development program will be the ability to predict spatially and in time (even time-averaged) NOx, CO, hydrocarbon (HC), and soot levels in jet-fueled combustors. Such predictions, for even simple hydrocarbon fuels, require detailed chemical mechanisms with complex chain branching/chain termination routes. To be able to predict these quantities in systems burning jet fuel is an enormous task given the number of individual chemical components comprising practical fuel blends and the composition variability that may occur from batch-to-batch. Despite the nearly ubiquitous use of logistic fuels in military applications, efforts to model their chemical kinetic behavior have been modest; however, given the long-term use of jet fuel, it is clear that a coordinated experimental and computational program is needed to develop chemical models that can be used within a larger research and development program.

This report discusses the results of a joint experimental and computational program that was initiated to test the feasibility of surrogate formulations of JP-8 capable of matching overall properties of the complex fuel and more detailed aspects of its combustion, such as flame structures. Specifically, the structure of two sets of flames was studied: a *nonsooting* CH_4 counterflow diffusion flame doped with 1000 ppm of either jet fuel or a 6-component surrogate and a well-defined baseline C_2H_4 *flame under incipient sooting conditions* perturbed with the addition of 2000 ppm by mole of either jet fuel or two surrogates, the 6-component Utah/Yale blend and a two-component Aachen surrogate. The research activity resulted in three peer-reviewed publications [1-3]. Key findings of the work, recent activity, and plans for the immediate future are summarized briefly. Further details are in the original publications. The work carried out was designed to provide a better understanding of the combustion of jet fuel to benefit both commercial and military users.

EXPERIMENTAL SETUP

The experimental setup consisted of a counter-flow burner with a nitrogen shroud shielding the flame from room drafts. Figure 1 shows a schematic of the experimental set-up. An electrospray vaporized the liquid fuel into an inert hot stream. Samples of the gas were extracted from the flame through a small silica probe. The chemical analysis was performed by a gas chromatograph (GC) (Agilent 6890A) equipped with thermal conductivity (TCD), flame ionization (FID) and mass spectrometry detectors (MSD) (Agilent 5973N). The instrument can separate and quantify N_2, O_2, CO, CO_2, light gaseous hydrocarbons, and higher hydrocarbons up to C_{14}, and even higher.

The GC data were post-processed by identifying the species by both the column retention time and the molecule specific spectrum. GC/MS analysis produced a wealth of information but had one main drawback: it took a very long time, on the order of at least one hour, to complete an analysis for a single location. A full flame dataset would entail a tedious procedure that lasted in excess of 30 hours. To ease the protocol of the chemical analysis, an automated sampling system was developed, along the lines of [4] to allow for sampling/storing using two multiposition valves, two pneumatic-actuated injection valves, and a battery of sampling loops, as shown in Fig.1. Thanks to this improvement, collecting samples from a flame required at most three hours of operator work during which the flame had to run continuously. This dramatic gain in the implementation of the experiment opened the doors to the systematic study of flame structures with relative ease.

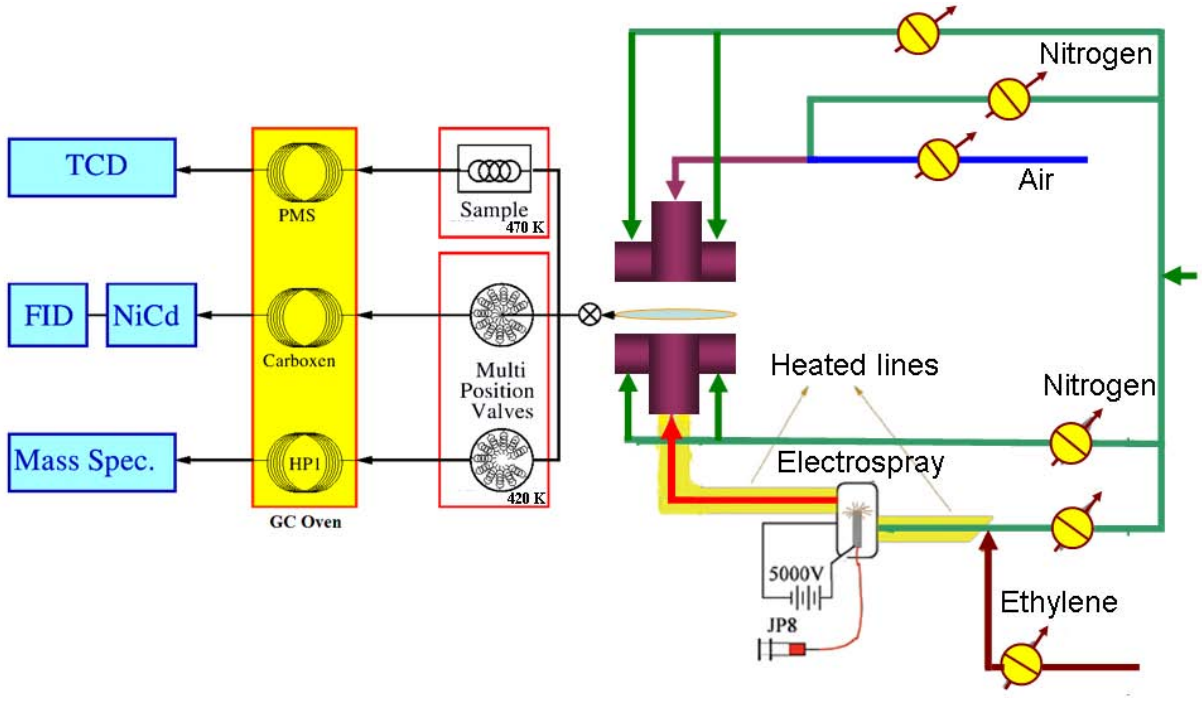

Fig. 1. Schematic of the experimental setup. In the nonsooting flames, ethylene is replaced with methane as the base fuel

SELECTION OF FLAMES

There were several options to compare flames with different composition. The overall objective was to use the flame as a well-controlled chemical reactor. In principle, it was advantageous to use a baseline flame, such as a methane or ethylene diffusion flame, as a reference flame with a prescribed velocity and thermal field and then to perturb such a flame with known amounts of either jet fuel or surrogates. This approach, advocated by McEnally et al. [5], has the following advantages: i) it minimized the potential of vapor condensation since the partial pressure of the condensable components was very modest; ii) critical (non-chemical) variables, such as temperature and velocity, can be measured once on the baseline flame without the need of repetitious measurements on each chemically perturbed flame; iii) probe-induced perturbation can be studied systematically on the simple baseline flame, since the fluid dynamic interaction of the intrusive probe and the flame was the same as when an additive was introduced. Residence time and temperature can be controlled by the flame strain rate and by the feed stream composition, respectively.

To span a sufficiently wide range of conditions, two sets of flames were considered: a highly diluted *methane* baseline flame doped with 1000 ppm of jet fuel or a surrogate under *non-sooting* conditions, with stoichiometric mixture fraction $z_f = 0.76$ and an *ethylene* baseline flame, since C_2H_4 has a greater soot propensity than CH_4 so that its boundary conditions can be adjusted with ease for it to be at the onset of soot formation. To that end, z_f was decreased to 0.18. Such a value ensured that the flame located itself on the *oxidizer* side of the stagnation plane and oxidation of soot precursors was avoided, unlike the previous set of flames. Details of the flame compositions are in Tables 1 and 2.

The jet fuel was provided by Wright-Patterson Air Force Base (POSF No. 4658). To account for the considerable variability in the composition of jet fuel from different refineries, an “average” jet fuel was synthesized by mixing 5 Jet A fuels from different U.S. manufacturers. The composition of that blend in vol% was: 55.2% paraffins (n- and i-), 17.2% monocycloparaffins, 12.7% alkyl benzenes, 7.8% dicycloparaffins and 4.9% indans and Tetralins. The balance, ≈ 2%, was in naphthalenes and trycylcoparaffins. The surrogate was the six-component blend of well-known hydrocarbons, as used in [6], with the following molar composition: 10% iso-octane (C_8H_{18}), 20% methylcyclohexane (C_7H_{14}), 15% *m*-xylene (C_8H_{10}), 30% *n*-dodecane ($C_{12}H_{26}$), 5% tetralin ($C_{10}H_{12}$), and 20% tetradecane ($C_{14}H_{30}$). This surrogate had the same components as the Utah surrogate [6], but the abovementioned percentages are on a *molar* basis rather than in volume percent, which amounts to a lower concentration of aromatics and larger concentration of aliphatics as compared to the composition of the Utah surrogate. It is referred to as the Utah/Yale surrogate in the remainder of the report. In the experiments on incipiently sooting flames the two-component Aachen surrogate also was used for comparative purposes [7]. A photograph of the baseline ethylene flame doped with the Utah/Yale surrogate is shown in Fig. 2. A layer of orange luminosity.

Fig. 2. Photograph of an incipiently sooting flame

Table 1: Boundary Conditions for the nonsooting methane-based flames

		Flame A	**Flame B**	**Flame C**
Fuel Side	Molar Composition			
	N_2	0.897	0.902	0.902
	CH_4	0.103	0.097	0.097
	C2-C5 alkane impurities	232 ppm	218 ppm	218 ppm
	Jet fuel ($C_{11}H_{21}$)		992 ppm	
	Methyl-Cyclohexane			200 ppm
	Iso-Octane			100 ppm
	m-Xylene			150 ppm
	Tetraline			50 ppm
	Dodecane			300 ppm
	Tetradecane			200 ppm
	Mass Flux (g/min/cm^2)	2.80	2.97	2.97
	Temperature (K)	379		
Oxidizer Side	Molar Composition			
	N_2	0. 227		
	O_2	0. 773		
	Mass Flux (g/min/cm^2)	3.19	3.42	3.42
	Temperature (K)	340		
	Strain Rate (s^{-1})	134	144	144
	z_f	0.76		

Table 2: Boundary conditions for the incipiently sooting ethylene-based flames

		Flame A Baseline	**Flame A*** Equal Carbon	**Flame B** Jet Fuel	**Flame C** Utah/Yale Surrogate	**Flame D** Aachen Surrogate
Fuel Side	Molar Composition					
	N_2	0.7278	0.7280	0.7340	0.7339	0.7339
	C_2H_4	0.2722	0.2719	0.2641	0.2641	0.2641
	C2 (Ethane) impurities	637 ppm	636 ppm	618 ppm	618 ppm	618 ppm
	Jet Fuel^{+} ($C_{11}H_{21}$)			1953 ppm		
	Methyl-cyclohexane				394 ppm	
	Iso-Octane				197 ppm	
	m-Xylene				295 ppm	
	Tetralin				98 ppm	
	n-Dodecane				591 ppm	
	n-Tetradecane				394 ppm	
	Total=				1970 ppm	
	1,2,4-trimethylbenzene					450 ppm
	n-Decane					1520 ppm
	Total=					1970 ppm
	Mass Flux (g/(cm^2.min))	1.619	1.683	1.684	1.683	1.682
	Temperature (K)	407	407	407	407	407
Oxidizer side	Molar Composition					
	N_2	0.8070	0.8070	0.8070	0.8070	0.8070
	O_2	0.1843	0.1843	0.1843	0.1843	0.1843
	Mass Flux (g/(cm^2.min))	1.891	1.925	1.925	1.925	1.925
	Temperature (K)	370	370	370	370	370
	Strain Rate (s^{-1})	89.9	85.2	92.3	92.3	92.3
	z_f	0.18	0.18	0.18	0.18	0.18

is visible underneath the flame chemiluminescence.

ONE-DIMENSIONAL COMPUTATIONAL MODEL

The nonsooting CH_4 flames were modeled computationally. The form of the describing equations for the counterflow flame model is well documented and presented in detail elsewhere (see, e.g., [8,9]). The counterflow problem was modeled by considering a similarity solution of the two-dimensional conservation equations of mass, momentum, species, and energy, valid along the stagnation point streamline. The resulting set of equations was written in terms of a nonlinear boundary value problem on a fixed spatial domain. Submodels for the thermodynamic and transport quantities, the chemistry, and the divergence of the radiative flux were evaluated using highly optimized libraries [10] and an optically thin radiation model [11]. In all cases, the software developed at Yale was used to study these problems on machines that included an 8-cpu AMD Opteron cluster equipped with 32GB of RAM and two four-way IBM 44P-270 systems running Linux. All computational systems were connected to a high-speed 1.2 TB RAID array via gigabit Ethernet links.

PRINCIPAL RESULTS

The experimental dataset provided a glimpse of the pyrolysis and oxidation behavior of jet fuel in a diffusion flame, as shown in Fig. 3. The addition of the jet fuel resulted in the fragmentation of heavier C7-C12 alkanes to lighter ones, the onset of C2-hydrocarbons, and the appearance of peak aromatic concentrations that were capable of withstanding higher temperatures as the location of the peak temperature was approached. This sequence was in line with the anticipated kinetic behavior based on thermal decomposition of large alkanes to smaller fragments and the survival of ring-stabilized aromatics at higher temperatures. The data for C7-C12 alkanes were consistent with typical decomposition of large alkanes with the surrogate(s), and reasonably good qualitative agreement with jet fuel in their pyrolysis trends was observed. More quantitative agreement was difficult to achieve because of the complex chromatograms of jet fuel with overlapping peaks due to isomerism. The computational results were in reasonably good agreement with the experimental data of the surrogate-doped methane-based flame. Preliminary comparison with the incipiently sooting ethylene flames revealed discrepancies even in the baseline (nondoped) flame, which is still under investigation.

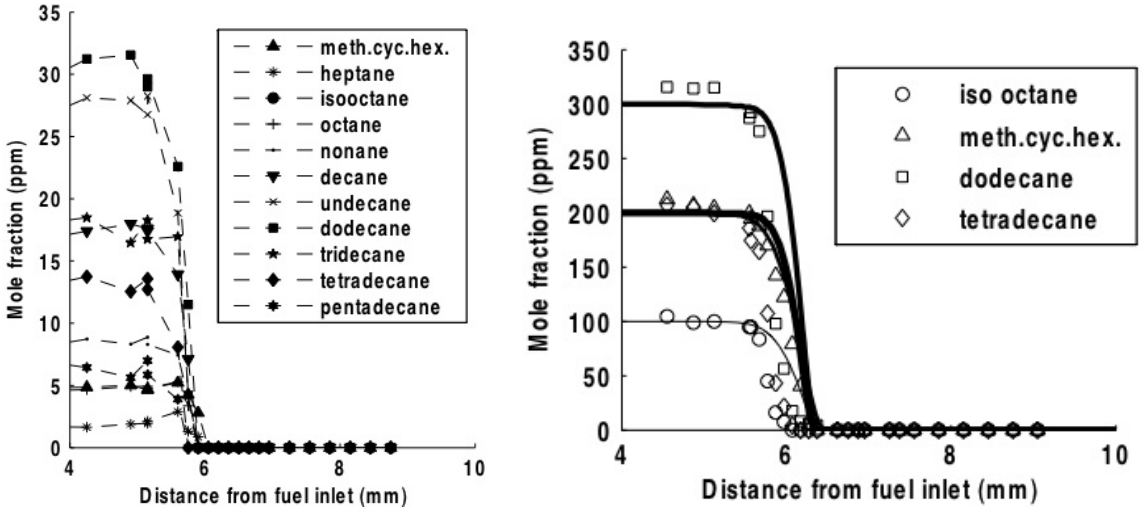

Fig. 3 Profiles of molar fractions of C7-C15 Alkanes in nonsooting methane-based flames (see Table 1 for details): left) Flame B (full symbols); right) Flame C (open symbols (experimental), solid lines (computational)

In the methane-based nonsooting flames there was a significant discrepancy in the aromatics (e.g., benzene and toluene) between jet fuel and one of the surrogates. Under the more relevant situation of incipient sooting there was good agreement between the jet fuel-doped and the surrogate-doped flames with respect to the location and magnitude of the benzene mole fraction peak, with the Aachen surrogate performing slightly worse and producing about 20% less benzene than the others (Fig. 4). Comparison of toluene mole fractions showed also reasonably good agreement between the flames, with the Aachen surrogate still underperforming and underpredicting the peak magnitude by almost 30%. Nevertheless, the somewhat worse, but still adequate, performance of the Aachen surrogate was compensated by its simplicity, since it

consists of only two components as compared to the 6 components of the Utah/Yale surrogate. The reason why attention was focused on benzene and toluene was that they are the two aromatic compounds that could be measured cleanly in all of the doped flames; therefore, they could be used as tracers of aromatic and soot formation. Figure 5 illustrates how these compounds are related to the formation of the two-ring aromatic naphthalene, which is a critical bottleneck to soot formation. Benzene is an intermediate in the growth of aliphatics (e.g., methylcylcohexane, iso-octane, and dodecane) to naphthalene, and toluene is a byproduct of the growth of n-alkylbenzenes (e.g., ethylbenzene, propylbenzene) to naphthalene via benzyl radical. Toluene was chosen instead of the benzyl radical since radicals cannot be detected.

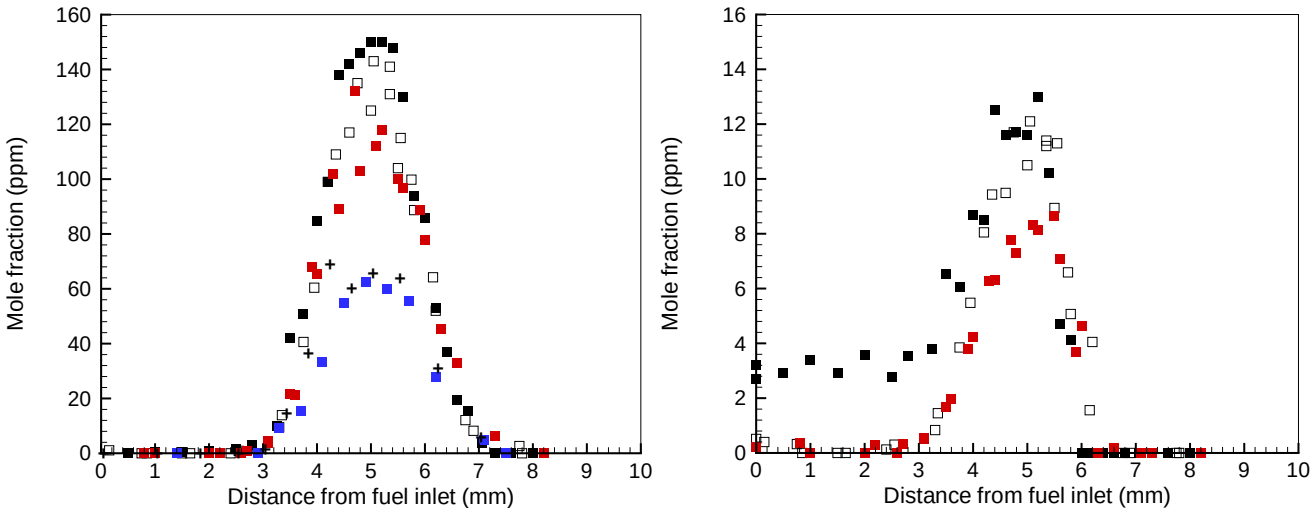

Fig. 4. Left: comparison of profiles of benzene mole fraction in incipiently sooting ethylene based flames (see Table 2 for details): Flame B (full black symbols), Flame C (open symbols), Flame D (red symbols), Flame A (blue symbols) and Flame A* (+). Right: comparison of profiles of toluene mole fractions for the same set of flames: Flame B (full black symbols), Flame C (open symbols) and Flame D (red symbols).

Acetylene (Fig. 6) in the incipiently sooting flames presented a unique behavior, with peak concentrations nearly 19 times larger than in the non-sooting flames, as expected, since acetylene is a major contributor to soot formation. Furthermore, the profiles showed a multimodal behavior, with a first local minimum that may be attributable to acetylene participation in the formation of soot precursors such as benzene and other large pyrolysis products and a subsequent local minimum, which may be the result of its participation in surface growth of soot particles.

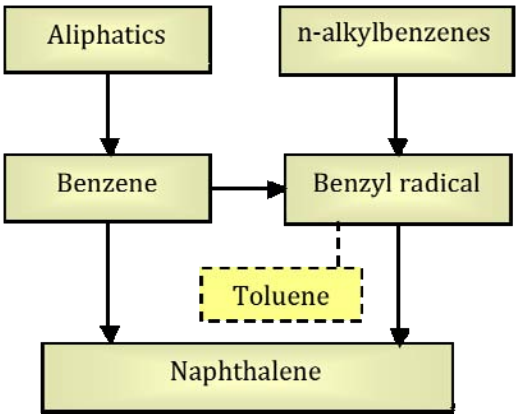

Fig. 5. Global pathways of naphthalene formation

A major challenge was identified in the quantification of the jet fuel components whose GC/MS analysis is at present qualitative and incomplete, as revealed by the fact that roughly only 22% of the overall carbon introduced as liquid fuel was recovered by the analysis (Fig. 7).

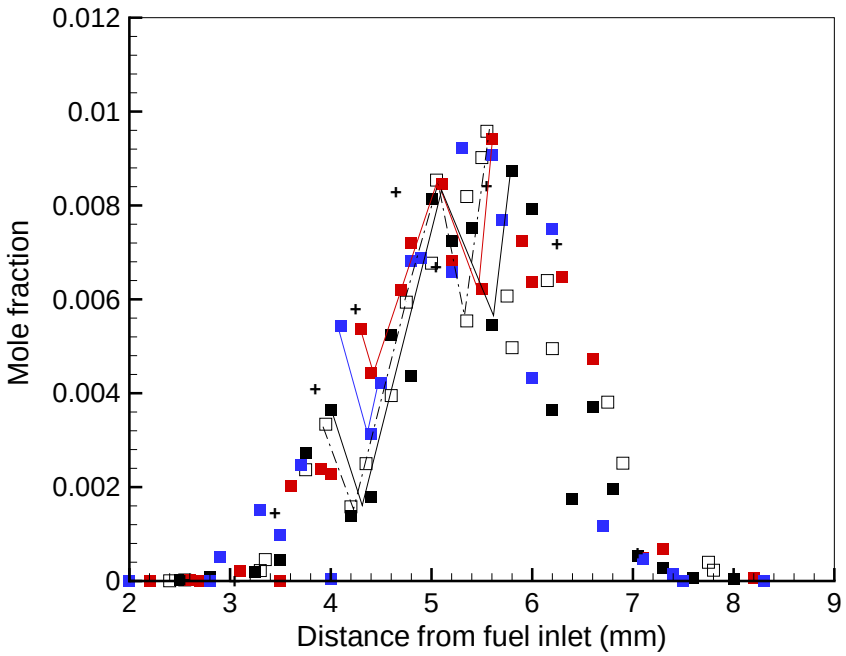

Fig. 6. Profiles of molar fractions of acetylene in the incipiently sooting ethylene-based flames (see Table 2 for details): Flame B (full black symbols), Flame C (open symbols), Flame D (red symbols), Flame A (blue symbols) and Flame A* (+).

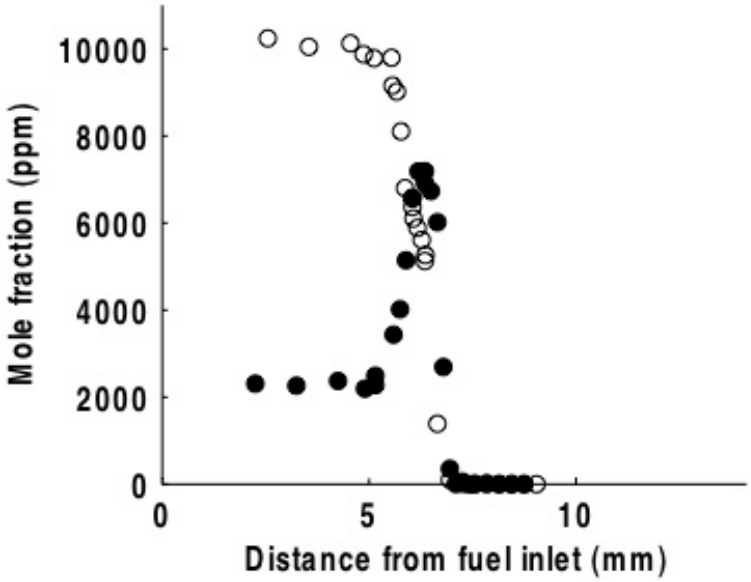

Fig. 7. Total carbon mole fraction in the nonsooting methane-based flames (see Table 1 for details): Flame B (full symbols) and Flame C (open symbols) (experimental), excluding the contribution from major products such as CO and CO_2, and their primary source, CH_4.

The intrusiveness of the quartz microprobe was quantified by laser-induced fluorescence visualizing the shift in OH concentration due to the presence of the probe. This shift was found to be ≤ 0.6 mm and is considered rather modest since it amounted to approximately 10% of the physical domain where chemistry played a role.

PARALLEL COMPUTING METHODOLOGY

An effort was begun to generate a program to compute JP-8 coflow diffusion flames using parallel computing methodologies. The parallel implementation utilized MPI Fortran interprocess communication libraries. The algorithm partitions the computational grid over N_{proc} distributed memory processors via a strip decomposition method following the work of [12-13]. The boundaries of each of the N_{proc} subdomains were oriented perpendicular to the dominant (axial) flow direction (see Fig. 8). Of the available processors, one master processor was chosen, leaving N_{proc} -1 slave processors. The N_z grid rows were divided among the available processors (including the master). If they did not divide evenly, the remaining mod[N_z/N_{proc}] grid rows were distributed among the slave processors, thus ensuring a more equitable distribution of tasks, as the master processor was responsible for some additional overhead tasks throughout the computation. The number of grid rows local to a given processor is denoted by N_{zl}, and the local number of grid points is denoted by N_{ptsl} ($N_{ptsl} = N_r \times N_{zl}$). Each processor was assigned an index (N_{rank}) ranging from 0 (the master processor) to N_{proc} -1. The master processor was assigned to the bottom partition of the domain, which contained the inflow plane, the processor with N_{rank} = 1 was assigned the partition above that, and so on, until the processor with $N_{rank} = N_{proc}$ -1 was assigned the topmost partition, which contained the outflow plane (see Fig. 8).

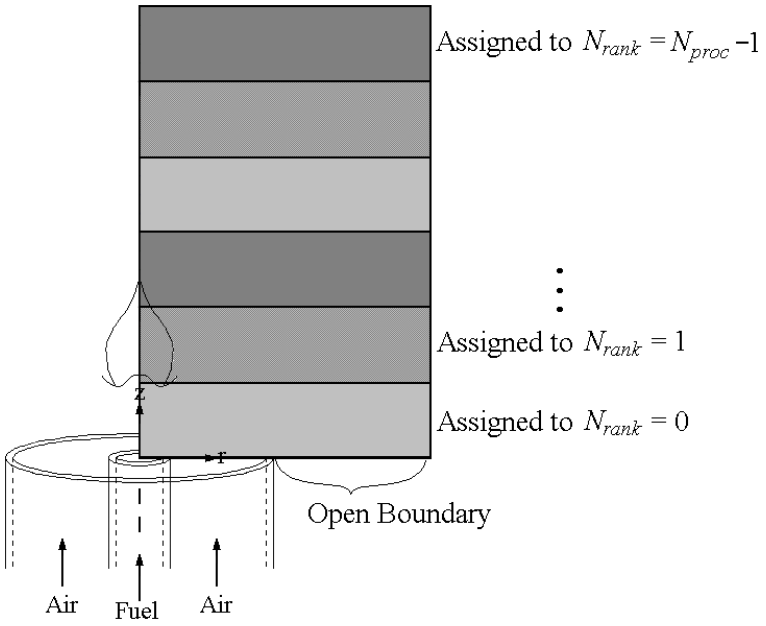

Fig. 8. Schematic representation of a strip-decomposed grid overlaid on top of the coflow flame configuration (not drawn to scale). In the image, the grid has been arbitrarily decomposed into N_{proc} = 6 subdomains.

The bulk of the computational cost lay in forming and solving the linear system associated with Newton's method, with key processes being evaluation of the residual vector $F(\bar{S}^K)$ and the Jacobian $J(\bar{S}^K)$. Residual formation is a non-sequential process, and thus each processor can form simultaneously the residuals in its assigned subdomain. In addition, the same is true for Jacobian formation once the residuals and residuals of the perturbed solution are known locally.

The only challenge of dividing residual formation and storage among the available processors concerns the boundaries of the subdomains. Each subdomain contained four boundaries: the symmetry axis, the far field boundary, a bottom horizontal boundary, and a top horizontal boundary. The processor assigned $N_{rank} = 0$ evaluated residuals associated with the inflow boundary condition (BC) (as its bottom boundary), and the processor assigned $N_{rank} = N_{proc} - 1$ evaluated residuals associated with the outflow BC (as its top boundary). The remaining horizontal boundaries are referred to as 'artificial boundaries'. To form the residuals of the describing equations at grid points along an artificial boundary, the solution vector, as well as the chemical, thermodynamic, and transport properties at the row immediately upstream (downstream) of a subdomain's lower (upper) artificial boundary, must be known locally. This situation is achieved by storing the entire current solution vector, $\bar{S}^K$, on each processor and by each processor evaluating chemical, thermodynamic, and transport properties at the grid row immediately upstream and immediately downstream of each artificial boundary. Thus, these properties are calculated and stored at one additional grid row for the inflow and outflow subdomain (for $N_{rank} = 0$ and $N_{rank} = N_{proc} - 1$, respectively) and at two additional grid rows for all interior subdomains.

A similar difficulty arose during Jacobian formation. The perturbation of $\bar{S}^K$ at a grid point along an artificial boundary generated entries in three upper (lower) block-diagonal bands of $J(\bar{S}^K)$ corresponding to the adjoining upstream (downstream) row. Thus, to form the entire Jacobian properly, residual evaluations involving solution perturbations occurred on a given processor at the rows just upstream (downstream) of the lower (upper) artificial boundaries. This requirement extended the region of transport, chemical kinetic and thermodynamic property evaluation and storage to two rows upstream (downstream) of each lower (upper) artificial boundary.

Once the portion of the Jacobian and right-hand-side vector $\left(-F(\bar{S}^K)\right)$ corresponding to a given processor were known on that processor, the linear Newton equations can be solved on that processor's assigned subdomain using a parallel implementation of the serial preconditioned Bi-CGSTAB solver [14]. The parallel implementation of Bi-CGSTAB was straightforward and required only global reductions and globally synchronized communication, both of which were handled easily by the MPI libraries; however, for the Bi-CGSTAB procedure to calculate the Newton correction vector over a given grid row, the Jacobian entries corresponding to the immediate upstream and downstream grid rows must be known. Therefore, the required region of transport, chemical kinetic, and thermodynamic property evaluation and storage was extended to a third row upstream (downstream) of each lower (upper) artificial boundary, and the region of residual evaluation was extended to a second row upstream (downstream). See Fig. 9. Computational tests are currently underway.

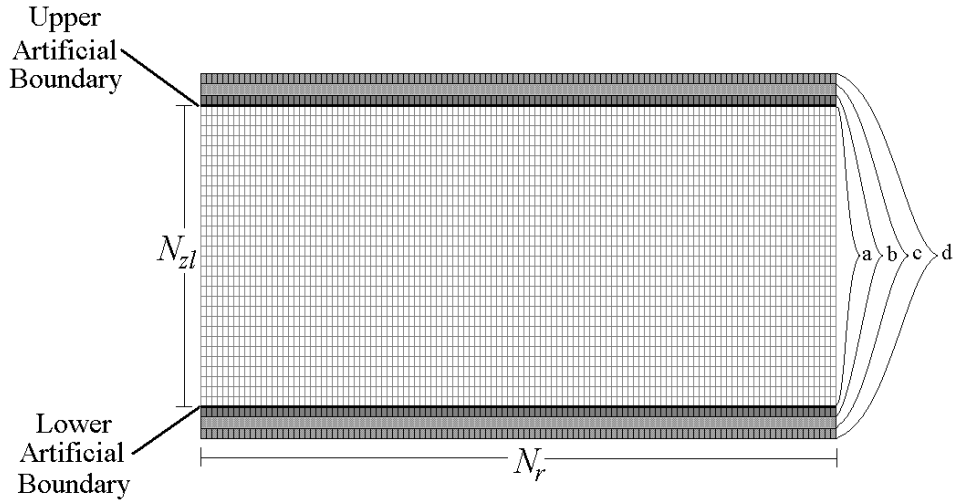

Fig. 9. Schematic representation of a strip-decomposed interior subdomain, indicating regions where (a) the Newton correction is calculated, (b) the Jacobian matrix must be known, (c) the residual components must be known, and (d) the chemical kinetic, transport, and thermodynamic properties must be known. (Actual computational grid is nonuniform.)

FUTURE ACTIVITY

Future activity is developing along multiple fronts:

- Flames doped with individual components of the surrogates will be considered and compared with the numerical model in an effort to sharpen the chemistry model, in collaboration with Dr. Charlie Westbrook;
- A high-pressure system will be developed to conduct similar studies at pressures as high as 40 atm. An existing system, developed under NSF sponsorship for soot studies, will be retrofitted to operate with liquid fuels and the storage loop system with which the GC/MS off-line analysis is implemented will be modified to make it transportable so that samples from the high-pressure facility can be analyzed.
- Efforts to make the analysis of jet fuel flames more quantitative will be pursued by examining a LC/MS option.
- JP-8 coflow diffusion flames will be computed using the parallel solution methodology.

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Personnel Supported:

One month of summer support was budgeted for Professor A. Gomez and one month for Professor M. Smooke.

One graduate student, Luca Tosatto, was supported on the grant.

Publications:

L. Tosatto, H. Bufferand, B. La Mantia, and A. Gomez, "Experimental and Numerical Study of a JP-8 Surrogate Counterflow Diffusion Flame," *Proceedings of the Combustion Institute*, **32**, 2009.

H. Bufferand, L. Tosatto, B. La Mantia, M. D. Smooke, and A. Gomez, "Experimental and Computational Study of Methane Counterflow Diffusion Flames Perturbed by Trace Amounts of Either JP-8 or a Six-Component Surrogate. Part 1: Non-Sooting Flames," *Comb. and Flame*, **156,** (2009)

S. Jahangirian, C. S. McEnally, and Alessandro Gomez**,** "Experimental Study of Ethylene Counterflow Diffusion Flames Perturbed by Trace Amounts of JP-8 and Jet Fuel Surrogates. Part 2: Incipiently Sooting Flames," *Comb. and Flame,* **156**, (2009).

Interactions/Transitions:

Discussions were held with Dr. Tim Edwards (AFRL) at the Surrogate Fuels Workshops in USC (February 2006), Washington, DC (June 2006), Reno, NV (January 2007, 2008), Boulder, CO (June 2007) and at the Fuels Summit at NIST (September 2008). They focused on the composition of JP-8 surrogates and the role of aromatics in surrogate blends for JP-8. Dr. Edwards has also supplied a JP-8 fuel blend for further testing.

Presentations and Meetings:

a. Surrogate Fuels Workshop, USC, February 2006
b. 11th International Meeting in Numerical Combustion, Granada, Spain, April 2006
c. AFOSR Contractors Meeting, Washington, DC, June 2006
d. Surrogate Fuels Workshop, Washington, DC, June 2006
e. 31st International Combustion Symposium, August 2006.
f. Surrogate Fuels Workshop, Reno, NV, January 2007
g. US Combustion Meeting, San Diego, CA, March 2007
h. AFOSR Contractors Meeting, Boulder, CO, June 2007
i. Surrogate Fuels Workshop, Boulder, CO, June 2007
j. Surrogate Fuels Workshop, Reno, NV, January 2008
k. 12th International Meeting in Numerical Combustion, Monterey, CA, March 2008
l. Joint Propulsion Conference, Hartford, CT, July 2008
m. 32nd International Combustion Symposium, Montreal, Canada, August 2008
n. Fuels Summit, NIST, Gaithersburg, MD, September 2008

New Discoveries:

None

Honors/Awards:

a. Fellow, AIAA (M. D. Smooke)
b. Program Co-Chair, 32nd International Combustion Symposium, Montreal, Canada (M. D. Smooke)
c. Elected to the Connecticut Academy of Science and Engineering (M. D. Smooke)
d. Yale College Teaching Prize in the Sciences and Engineering, (M. D. Smooke)
e. Yale University Graduate Mentor Award (M. D. Smooke)